Efficient Hydrographic Survey Planning Using an Environmentally Adaptive Approach

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Abstract – This paper examines the impact of adaptive line running on survey planning. Since the progression of an adaptive survey, i.e. the shape and position of the track lines, depends upon the topography and other factors, simulations must be used to estimate survey time. We see that the introduction of adaptive surveying can complicate this process due to sometimes dramatic differences in survey time estimates depending upon the alternatives chosen to execute a survey. A brief introduction is given to an implemented adaptive survey approach and a simulator developed for making survey time estimates. Results of simulation time estimates for a US Northeast coast survey are presented that reveal some of the unexpected dependencies that exist with adaptive surveys. Finally, a closer examination is provided regarding how user specified survey parameters may impact overall survey time.

I. INTRODUCTION

This paper introduces an approach to hydrographic survey planning for environmentally adaptive surveys. Environmentally adaptive surveys [1] use track lines that are not necessarily straight or parallel and are adapted to the depth of the water to minimize survey time. While this approach can reduce actual survey time as much as 30%, it makes survey time estimation challenging since the shape and location of each consecutive track line is dependent both upon the bottom's shape and the previous track line position. The approach to survey planning presented here uses available digital terrain data in the area of interest coupled with a simulator that is capable of emulating vessel and sonar characteristics. These are used to predict the track lines that would be generated during the survey and to estimate the total survey execution time.

Section II briefly describes the AutoSurvey approach to adaptive surveys and the design of the AutoSurvey simulator developed for adaptive survey planning. In Section III we discuss the results of planning for a U.S. EEZ survey on the northeast Atlantic coast where time estimates were made by NOAA, the Naval Oceanographic Office and the AutoSurvey simulator. These simulations revealed some unexpected survey time dependencies resulting from the interaction between user-determined survey parameters and the shape of the bottom.

These results prompted further simulation studies, presented in Section IV, that were conducted to better characterize those dependencies. It was found that total survey time

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14. ABSTRACT
This paper examines the impact of adaptive line running on survey planning. Since the progression of an adaptive survey, i.e. the shape and position of the track lines, depends upon the topography and other factors, simulations must be used to estimate survey time. We see that the introduction of adaptive surveying can complicate this process due to sometimes dramatic differences in survey time estimates depending upon the alternatives chosen to execute a survey. A brief introduction is given to an implemented adaptive survey approach and a simulator developed for making survey time estimates. Results of simulation time estimates for a US Northeast coast survey are presented that reveal some of the unexpected dependencies that exist with adaptive surveys. Finally, a closer examination is provided regarding how user specified survey parameters may impact overall survey time.

15. SUBJECT TERMS
adaptive line running, survey planning, track lines

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could be significantly affected by factors including the type of line running algorithm chosen, shape of the survey boundary and selection of the first track line. These results indicate the importance of running multiple simulations prior to the execution of a survey in order to select parameters that minimize survey time. Analysis of the quantitative results from a series of simulations provides us with a coherent approach to simulation analysis that must be considered in order to optimize surveys that use adaptive line running.

II. AUTOSURVEY

The AutoSurvey system was developed by the Naval Research Laboratory for optimization of hydrographic surveying. Since the swath width of a hull-mounted multi-beam bathymetry system can vary drastically with depth and other ocean conditions, optimal deployment of survey vessels is typically not achieved using standard 'ladder' surveys that employ a series of uniformly spaced track lines. AutoSurvey uses adaptive navigation to reduce deployment time by computing waypoints for the next survey line in real time, based on the actual sonar coverage achieved with the previous line. Compared to ladder survey plans adaptive navigation has shown reduction in survey time of 30% and greater in simulation and sea trials. As shown in Fig. 1, three line generation methods are provided: 1) adaptive parallel - uses parallel but unevenly spaced lines, 2) linear regression - uses lines that are straight but whose spacing and angle are adapted, and 3) piecewise linear - uses segmented lines. Typically the piecewise linear method provides the greatest reduction in survey time. While linear regression and adaptive parallel are less efficient over rough terrain, they provide straight track lines that are more suitable when a tow is employed, and adaptive parallel ensures a specific heading orientation that may be important in higher sea states. A more in depth discussion of AutoSurvey is available in [2].

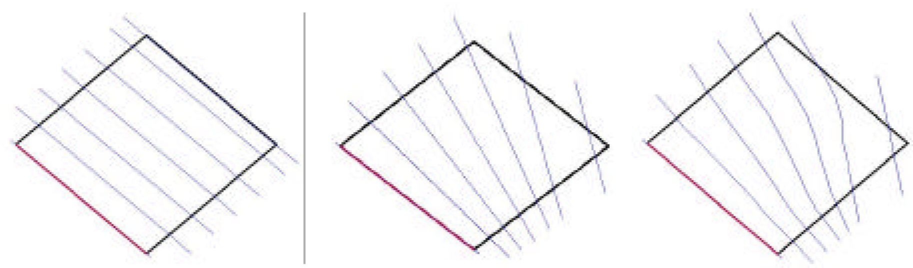


Figure 1. These images depict a survey area (black/red lines) showing lines run (blue lines) using the three different line methods; the red line along one edge of the survey area is the first line run. The methods are (from left to right) adaptive parallel, linear regression and piecewise linear.

The AutoSurvey simulator was developed to better estimate the amount of time hydrographic surveys using the AutoSurvey line running methods would require, and a block diagram of the simulator is shown in Fig. 2. The simulator is composed of a survey navigation system for the simulated vessel, the vessel motion simulator, the sonar simulator and the AutoSurvey library. A simulation is initiated by defining the coordinates of a survey boundary and specifying one edge of that boundary as the first line to run. The survey navigation system, essentially an autopilot, uses the coordinates of the first line to run to issue vessel navigation commands to the vessel motion simulator.

The vessel motion simulator is a fast 2-degree of freedom simulation that moves the vessel along the desired track as directed by the survey navigation system. It accounts for speed, heading and turning rate. Modeling turning rate is important, especially for large vessels, to ensure that the simulation doesn't falsely allow the vessel to make instantaneous turns at the end of each survey line. In order for the vessel to stay on the intended survey track line, the simulation must then account for the time spent on lead-in and lead-out distances that are appropriate for the vessel size being considered and also for the impact of a towfish if used. In an actual survey lead-in and lead-out segments are added to each track line to give the vessel sufficient room to turn and line up with the next survey track. As discussed later in this article, the lead-in and lead-out segment lengths can have a significant impact on survey time estimates.

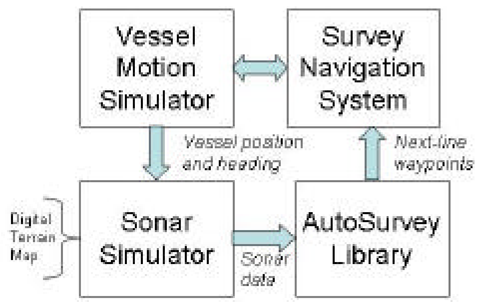


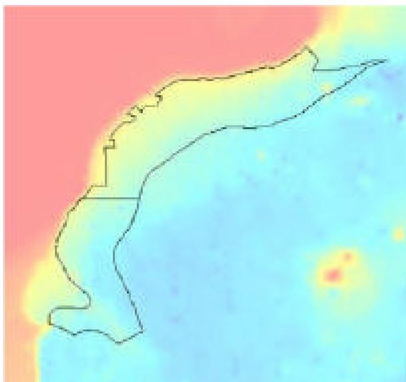
Figure 2. AutoSurvey Simulator block diagram.

Using a digital terrain map, the sonar simulator generates swath bathymetry data at a user specified ping rate as the simulated vessel moves along its track. Sonar parameters that are modeled include total angular coverage, beam width/number of beams and maximum slant range, allowing the simulated sonar to mimic any generic multi-beam bathymetry system. The synthetic data generated by this module is used in real-time by the AutoSurvey™ library and in post-processing to analyze sonar coverage and data density [1].

At the end of the first track line the AutoSurvey™ library module is triggered and passed the synthetic sonar data. It uses this data to determine the extent of the sonar coverage and then generates the next track line waypoints using one of the 3 selected line methods discussed previously. These waypoints are then passed to the Survey Navigation module for execution of the next track line.

III. SIMULATION RESULTS

In December of 2001, the University of New Hampshire's Center for Coastal and Oceans Mapping/Joint Hydrographic Center (CCOM/JHC) embarked on the difficult task of determining the legitimacy of a possible extension to the Exclusive Economic Zone (EEZ) of the United States as stated under Article 76 of the United Nations Convention on the Laws of the Sea (UNCLOS) [3]. Their conclusions were that while an extension to the U.S. EEZ could be validated with current data there could be a high level of uncertainty as to what extent. They provided to the National Oceanographic and Atmospheric Administration (NOAA) a series of potential survey areas to be considered for obtaining high resolution bathymetry to support any possible request for such an extension. Of these potential survey areas, two were passed by NOAA to the Naval Oceanographic Office (NAVOCEANO) to develop survey planning estimations in addition to their own. Since the AutoSurvey™ Planner was being introduced to NAVOCEANO at this time it was used to develop estimations on these areas as well.



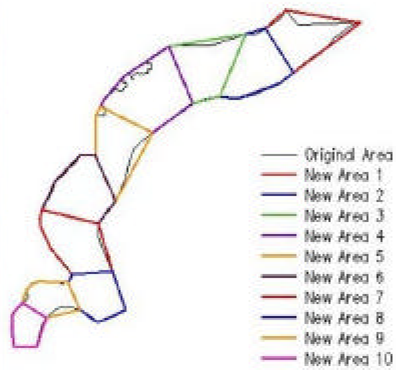


Figure 3. The survey area used for the most recent AutoSurve Planner simulations. The image on the left is the original areas back-dropped by the DTM data. The image on the right is the original areas broken down into sub-areas for the AutoSurvey™ runs.

The two areas are large tracts in the Atlantic along the Eastern United States that were laid out to cover the possible locations of the Foot of Slope (FOS), where the foot of the continental slope is defined as the point of maximum change of the gradient at its base [4]. The image on the left in Fig. 3 shows the two areas overlaying a Digital Terrain Map (DTM) that depicts the ocean depths. Combined, the areas were irregularly shaped and covered approximately 374 x 10^3 km^2 and ranged in depth from ~620 m to ~5,732 m, with a mean depth of ~3,847 m. The large size of this area proved to be cumbersome because running a simulation of this size could result in overwhelming processing times and file sizes, potentially pushing the file size limits of the 32-bit host operating system. Therefore, the large areas were broken down into smaller ones that approximately followed the boundary of the originals. The image on the right in Fig. 3 shows the dissection of the original areas. The division of the areas was approached carefully in an effort to maintain nearly the original shape while using fewer boundary points. This ensured that even though changes were made to the original areas, they would not be significant in the final simulation results. While not specifically addressed in this effort, large survey areas could commonly be expected to be subdivided into provinces according to the survey systems being employed and their respective operating ranges.

Survey simulations were run on each of the smaller areas to obtain time estimates for both inside and outside of the survey area (outside corresponds to time in turns). For all simulations a 120 degree swath width was assumed with a full ocean depth capable sonar and a vessel speed of 8 knots. All three line generation methods were used on each area in order to ascertain which method was the most efficient. This allowed a mix-and-match approach, where the most efficient method from each area was used to optimize the overall estimation. Initial quick calculations by NAVOCEANO and NOAA gave preliminary estimates of 140 and 80 days respectively (survey days were considered to be 20 hours long). More detailed calculations gave estimates of 110 days and 90 days respectively, and the AutoSurvey simulator produced an estimate of 96 days.

	Area 1	**Area 2**	**Area 3**	**Area 4**	**Area 5**	**Area 6**	**Area 7**	**Area 8**	**Area 9**	**Area 10**
Adaptive Parallel										
TI	218.61	208.88	561.66	400.27	221.11	259.44	198.88	112.22	96.66	82.50
TO	11.66	8.33	6.38	8.33	6.38	7.22	8.88	8.05	7.77	4.16
TT	230.27	217.22	568.05	408.61	227.50	266.66	207.77	120.27	104.44	86.66
Linear Regression										
TI	215.00	203.05	717.77	388.33	218.05	257.50	186.38	107.50	95.55	77.77
TO	11.94	8.05	17.77	7.50	6.11	5.27	9.44	7.50	7.77	4.72
TT	226.94	211.11	735.55	395.83	224.16	262.77	195.83	115.00	103.33	82.50
Piecewise Linear										
TI	197.29	195.93	351.18	366.85	215.51	234.68	179.45	106.85	90.62	72.38
TO	19.77	19.84	31.06	25.22	16.62	15.76	14.60	15.17	13.86	9.35
TT	217.06	215.77	382.25	392.08	232.13	250.45	194.06	122.02	104.48	81.73
Most Efficient	PL	LR	PL	PL	LR	PL	PL	LR	LR	PL

Table 1 - This table shows the time comparisons for the 10 simulation runs for the east coast area. TI, TO and TT are the time spent inside, outside and the total survey time, respectively (in hours). ME is the most efficient line method based on total survey time for each area.

Table 1 gives a break down of the time estimations obtained from each of the individual simulation runs. An unexpected result was that for many of the areas (2, 5, 8 and 9) linear regression proved to be slightly more efficient overall than the piecewise linear line method; it had previously been assumed that piecewise linear would always be the most efficient since its algorithm provides the best matching of the next track line to the shape of the current lines' swath edge. A detailed examination of the results reveals that piecewise linear is in fact more efficient inside the survey boundary, but for these areas the time spent in the turns outside of the survey boundary result in net less efficiency. This loss of efficiency was a result of the ‘fanning out’ of the ends of the survey lines due to the very large swath widths in these areas; while this is precisely what the piecewise linear method was designed to do, we see that in some situations it can result in very large transit times outside of the survey bounds to get from the end of one line to the beginning of the other.

The results of the simulation in area 3 show that piecewise linear resulted in a dramatically lower survey time than the other methods. This is the anticipated outcome, particularly in areas with a large deviation in water depth. As seen in figure 4, the shallow area in the top middle of the survey area cause adaptive parallel (right) to generate several lines that are close together in order to ensure no gapping over the shallow area. Piecewise linear (left) brought its lines in closer over that area but then fanned out on either side as the water became deeper. These results, plus other simulations that revealed a difference in efficiency depending upon which boundary edge was used as the starting line for an area, prompted further study to determine empirical methods for knowing when simulation of the possible options would be prudent to determine the most efficient approach to conducting a survey.

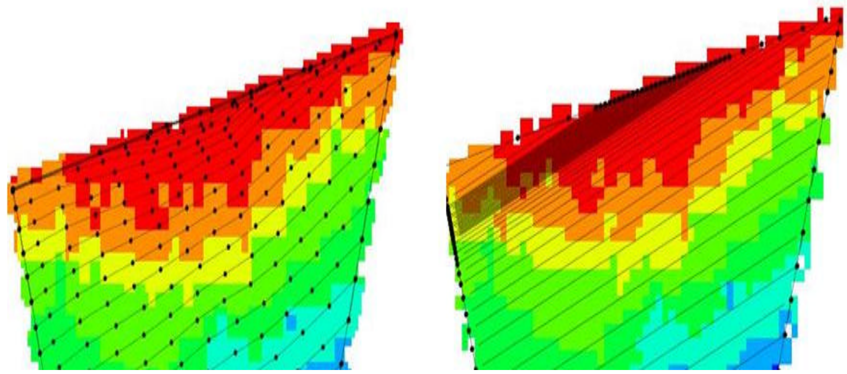


Figure 4. Track lines for Area 3. Piecewise linear is shown on the left, adaptive parallel on the right.

IV. PARAMETERS THAT IMPACT SURVEY TIME

The simulation results presented in the previous section show that for a specific topology and survey area the adaptive line method chosen can impact the total survey time. Besides the line method, the choice of the survey boundary shape and the first line to run can also impact total survey time. Let us consider a simplified case where we have a flat bottom, a survey area that is 100m by 1000m and a swath width of 100m. If we were to run the survey lengthwise then we would cover the entire area with a single 1000m line. If we run along the short leg we would require 1000m to cover the area in the survey boundary plus the additional distance required to make the 10 line turns. If we assume we need a 100m lead out and lead in for ship alignment then the total distance required to run the survey in this direction is approximately 3700m. This example is depicted in Fig. 5.

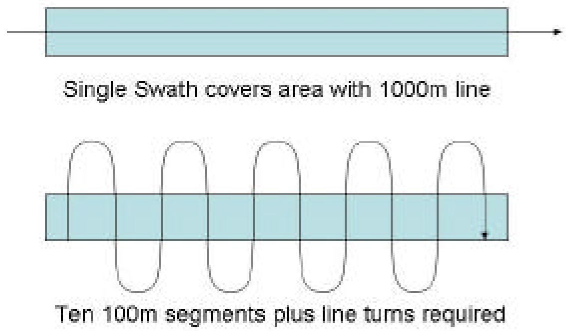


Figure 5. Impact of choice of first line to run on survey time

The previous example considers the simple case where the track line is always perpendicular to the boundary edge, but the shape of the boundary or the progressive orientation of adaptively generated lines can result in situations where the track line is not perpendicular to the boundary's edge. As portrayed in Fig. 6, this can also result in increased survey time. If the vessel were to start its turn at the survey boundary then the area inside the survey boundary shaded in yellow could be missed. As a result, we have to add an extra lead out distance D to ensure full coverage within the survey area. As the angle between the track line and survey boundary becomes shallow the length of D increases and could ultimately impact overall survey time. Consequently, we can see that if we have a situation where the track lines may not run perpendicular to the boundary then we need to account for an adaptive lead in/out distance in our planning.

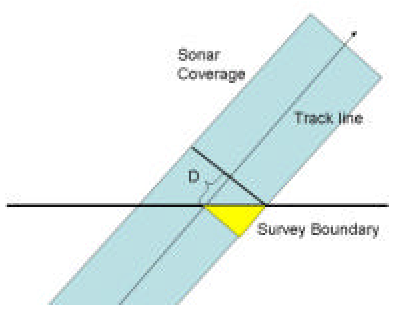


Figure 6. Impact of angle between track line and boundary edge

From this example we can clearly see that the shape of the survey boundary and our choice of the first line to run can have a significant impact on total survey time. We can readily deduce that if the boundary is equilateral that the choice of the first line will not impact survey time (again assuming the simplifying case of a flat bottom), but if the boundary is non-equilateral we should compute time estimates for the different first line options available.

With the examples presented thus far, we can see the potential need to compute several estimates for survey time considering different line methods and first line options in order to choose the most efficient. Since we prefer not to have to run simulations to test every possible case for every survey, we would like to have some guidelines to indicate when we need to run simulations to test multiple considerations. Table 2 provides a first attempt to quantify these considerations.

	Boundary Equilateral	Boundary Not Equilateral
Terrain Flat	Case 1: Line method – no First line – no	Case 2: Line method – no First line – yes
Terrain Not Flat	Case 3: Line method – may depend upon first line First line – yes	Case 4: Line method yes First line - yes

Table 2 Impact of line method and first line choices on survey time contrasted with boundary shape and terrain roughness.

In this table we are assuming that we have specified 100% coverage (adjacent swath edges butt up against each other) and that the survey vessel closely follows the intended track line. Note that the latter assumption is not typically true for shallow water (narrow swath) surveys where the motion of the vessel, not the shape of the bottom, can be the dominant factor in the shape of the swath. Also, the use of the term flat here means horizontal as opposed to smooth (such as a smooth but sloping bottom). For cases 1 and 2 when the terrain is flat, the swath width will be constant so the line method chosen will have no impact on the survey time – the lines generated by each of the 3 methods will always be straight and parallel. As discussed above, if the boundary is equilateral then the choice of first line has no impact on survey time. If not equilateral then the time in turns and the additional lead in/out needed for non-perpendicular boundary intersections can result in significantly longer survey time.

For cases 3 and 4 we consider non-flat terrains where the interaction between adaptive line methods, bottom shape and boundary definition can become quite complicated. To simplify, we will start with an equilateral boundary and a smooth sloped bottom whose gradient is parallel to a boundary edge. If we start the survey along an edge perpendicular to the gradient then we will end up with all 3 line methods generating adaptively spaced but straight lines that are also perpendicular to the gradient. Case 4 in table 2 will include all of the complexities of case 3 just discussed and will additionally include those discussed for case 2. Consequently, we can see that if the bottom is rough and/or the boundary shape deviates significantly from being equilateral, we should conduct simulations to be able to quantitatively compare alternatives.

V. CONCLUSIONS

In this paper we have examined the process of making estimates of survey time when adaptive line running, i.e. track lines that are dynamically generated based on actual sonar coverage, is used for hydrographic surveys. Simulations are used to generate the time estimates and the results presented reveal sometimes dramatic differences in survey time depending upon the user's choice of survey parameters. The interaction between these parameters including shape of the survey boundary, first line to run, bottom morphology and next-line generation method chosen are discussed as a guide to determine when additional simulations should be conducted to determine the optimal approach to surveying a particular area.

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